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Regulation of a Multi-Fleet Fishery

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Abstract: Optimum management of a particular fishery is discussed. For this purpose a multifleet deterministic bioeconomic model is developed and applied. It is illustrated the way in which an effort tax can achieve an optimum exploitation. Using the data from the North East Atlantic Cod (NEAC) fishery, optimum levels of stock, effort and tax by fleets are determined.

Key words: Multifleet fisheries, effort tax, cannibalism, optimum management

INTRODUCTION

Fisheries are managed because the consequences of uncontrolled fishing are seen as undesirable. Traditionally, the full utilization of fish stocks for profit maximization has been the key goal of fishery management and development, putting protection and conservation of the valuable ocean resources in the backseat. These consequences could include fishery collapse, economic inefficiency, loss of employment, habitat loss or decreases in the abundance of rare species. Fisheries scientists tried to provide advice that could be used to prevent the overexploitation or collapse of fished stocks. But, the increasing intensity of fishing throughout the world has had impacts on the marine ecosystem and these impacts are now the focus of many research and management progress.

The complexity of time evolutions of natural populations, due to nonlinear biological growth functions and the ecological complexity of interactions among species, gives rise to several difficulties in implementing suitable regulation policies that are able to combine economically and socially efficient exploitation with issues of sustainable exploitation. Indeed, these severe nonlinearities can present themselves at multiple levels and in multiple ways, due to nonlinear interactions between ecological and economic components and present a serious challenge to policy makers.

Traditionally, common property natural resources have been exploited freely by anyone. Anyone have had the right to exploit the resource and no one have had the right to deny somebody from the exploitation. The tragedy of the common occurs, when everybody thinks just his/her own benefit and ignores the impact of his/her own behavior on the others. At that time the resource is used more than the social optimum requires and the overuse could lead even to the extinction of the resource (Hardin, 1968).

Management actions can be divided into catch controls, effort controls and technical measures. Technical measures restrict the size and sex of fixed species that are caught or landed, the gears used and times when, or areas where, fishing is allowed. Gear restrictions, such as the size of mesh in traps and nets, control the minimum sizes at which fished species are caught. Mesh size restrictions can have unintended effects in multi-species fisheries.

Time and area closures can protect fished species at specific phases of their life history. Time closures can protect annual stocks until their production and quality is high, but also lead to market gluts at the start of the fishing season. These can cause prices to fall and force processors to invest in

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capacity that is idle for much of the year. Area closures may stimulate effort redistribution and increase fishing costs without reducing fishing mortality. Time and area closures have been most effective when used in conjunction with other measures such as catch and effort controls (Hannesson, 1998).

Catch controls also known as output controls, are intended to control fishing mortality by limiting the weight of catch that fishers can take. These include Total Allowable Catches (TAC) or quotas (Q), which are limits on the total catch to be taken from a specified stock, as well as individual quotas (IQ) and vessel catch limits where the TAC is divided between fishing units. In many cases, catch controls are really landings controls, since fishers may kill and discard unseen large numbers of fish of a size or quality that do not attract the highest prices in order to make the most money from their IQ. Clearly if such high grading takes place, the IQ will not directly control fishing mortality.

IQS restrict the catches of individual fisheries or boats. The sum of all IQS will equal the TAC. If IQS can be bought and sold by fishers then they are known as Individual Transferable Quotas (ITQ). A management system based on ITQs can not be adapted to all fisheries. It will also have a series of disadvantages, some of which had already been outlined by Copes (1986), which make their use inadvisable. ITQs have considerable difficulties in the management of multispecies fisheries (Garza-Gill *et al*., 2003).

Effort controls, also known as input controls, limit the number of boats or fishers who work in a fishery, the amount, size and type of gear they use and the time the gear can be left in the water. Effort controls may be also limit the size or power of vessels and the periods when they fish. The aim of effort control is to reduce the catching power of fishers and thus reduce fishing mortality. Cullen (2000) identifies and develops a range of possible criteria for determining the instruments (including taxes) which allow the external effects of fishing activity on the marine resource to be internalized. Furthermore and on a very concrete level, McCarty (2000) proposes an incentive mechanism using taxes in order to finance business investment in the fishing sector.

One of the most frequently mentioned regulator devices in the fishery economics literature is the use of a tax to reduce the amount of catch or fishing effort (Clark, 1990; Pradhan and Chaudhuri, 1999; Kar and Chaudhuri, 2003). Starting with open access setting the tax converts a situation of rent dissipation into one of rent capture. Despite its seemingly apparent potential for improving conditions, the use of a tax to regulate a fishery has not fared well in the political area (Johnson, 1995). Fishing effort is usually denoted as a function of the capital and labor inputs used to harvest fish. The objective of taxation is to reduce the amount of redundant effort and allow the fish population time to recover. If the tax rate is set correctly, either on fishing effort or on the harvest itself, the implicit rental value of the fishery resources will be maximized. The tax can achieve this objective, in part, because it alters the equilibrium stock level of the fish population. Actually the imposition of the tax generally the very rent that is sub sequentially collected by the taxing authority. But taxes have not been the regulatory instrument of choice. One obvious reason is that taxation does not benefit fishers and they have political clout in lobbying against taxation.

The aim of this study is to use a case study to illustrate the way in which a tax on fishing effort applied to a fishery leads to optimum exploitation of marine resources. We will focus on the case of a tax on effort given that a tax on catches is not advisable for fisheries in which the quantity of species discarded or thrown back into the sea is not known exhaustively (Garza-Gill *et al*., 2003).

We will, however, after presenting a general introduction of the model, simulate using the data from the North-East Atlantic cod stock. The fact that different vessel groups with diverse technology harvest on different age groups of cod. Interspecific predation or cannibalism is a well known behavioral trait found in a variety of animal populations (Polis, 1981). Cannibalism leads to a higher mortality rate and animals that practice it would then be at a competitive disadvantage with those who do not (Kaewamanee and Tang, 2003). This biological phenomenon is also expected to play a crucial role in the population dynamics of cod stocks (Bogstad *et al*., 1994; Linehan *et al*., 2001).

A detailed empirical model for any fishery is very difficult. For the NEAC fishery, the methods and results given in the study do not provide the full story but we believe it to be an important step toward a comprehensive bioeconomic model. It provides a approximate key levels of optimal harvesting and taxation. It is an efficient tool for investigating the changes in the optimal yield policies and allows us to compare harvesting policies.

DESCRIPTION OF THE FISHERY

The North East Arctic or Arcto-Norwegian stock is at present the world's largest population of Atlantic cod distributed in the Barent Sea area. This fishery has played an important economic role within the coastal communities for the past 100 years. This stock spawns in March and April along the Norwegian coast, about 40% around the Lofoten archipelago. Newly hatched larvae drift northwards with the coastal current while feeding on larval copepods. By summer the young cod reach the Barents Sea where they stay for the rest of their life, until their spawning migration. As the cod grow, they feed on krill and other small crustaceans and fish. Adult cod primarily feed on fish such as capelin and herring. The Northeast Arctic cod also shows cannibalistic behaviour. The stock size fell from its highest level in 1946 of 4.1 million tones to the lowest in 1981 of 75 million tones. However, the stock seems to be recovering from the depleted state in the 1990s due to improved management strategies. Estimated stock size was in 2004 1.6 millions tones. In 2003, ICES stated that there is a high risk of stock collapse if current exploitation levels continue and recommended a zero catch of Atlantic cod in the North Sea during 2004.

The cod is highly migratory species that can be divided into two sub-stocks, spawners and juveniles. The species is caught using coastal and trawl vessels. These fishing methods have different effects on the cod stock. Specially, trawling acts intensely on younger individuals (small cods), whereas the other fishing method mainly affect more mature cod.

THE MODEL

We consider the case where the fishery is a multi-fleet fishery. A two stage biomass model is used.

These equations may be represented as follows,

$$\frac{dx_1}{dt} = F(x_1, x_2) - h_1(q_1, E_1, x_1)$$
$$\frac{dx_2}{dt} = G(x_1, x_2) - h_2(q_2, E_2, x_2),$$

where x_1 and x_2 represent the biomass $F(x_1, x_2)$ and $G(x_1, x_2)$ are the growth functions and $h_1(q_1, E_1, x_1)$ and $h_2(q_2, E_2, x_2)$ are harvesting functions of the immature and mature sub-stock, respectively.

Given the price of fish to be p_i and the cost per a unit of fishing effort to be c_i, the following profit functions can be constructed:

$$\pi_i(E_i, x_i) = p_i h_i - c_i E_i, i = 1, 2.$$

A social optimum would be to maximize the discounted stream of profits realized within the fishery, subject to motion equations for the biomass. This can be illustrated as follows:

$$\underset{(E_1,E_2)}{\mathrm{Max}}\int_0^\infty e^{-\delta t}[\pi_1(E_1,x_1)+\pi_2(E_2,x_2)]dt,$$

subject to

$$\begin{aligned}&\frac{dx_1}{dt}=F(x_1,x_2)-h_1(q_1,E_1,x_1)\\&\frac{dx_2}{dt}=G(x_1,x_2)-h_2(q_2,E_2,x_2)\\&0\le E_i(t)\le E_{i\max},\\&x_i(t)>0,\ i=1,2.\end{aligned}\tag{1}$$

where δ is the instantaneous discount rate.

If $\lambda_1(t)$ and $\lambda_2(t)$ represent the current value of the shadow price of the immature and mature species, respectively then the current value Hamiltonian (Clark, 1990) associated with the optimal harvesting problem is given by

$$\begin{aligned}H&=(p_1h_1-c_1E_1)+(p_2h_2-c_2E_2)+\lambda_1(F(x_1,x_2)-h_1(q_1,E_1,x_1))\\&+\lambda_2(G(x_1,x_2)-h_2(q_2,E_2,x_2))\end{aligned}\tag{2}$$

Applying the Pontryagin maximum principle we obtain a system of equations that represent the first order conditions for this problem:

$$(p_1-\lambda_1)\frac{\partial h_1}{\partial E_1}=c_1\tag{3}$$

$$(p_2-\lambda_2)\frac{\partial h_2}{\partial E_2}=c_2\tag{4}$$

$$\dot{\lambda}_1=\delta\lambda_1-[(p_1-\lambda_1)\frac{\partial h_1}{\partial x_1}+\lambda_1\frac{\partial F}{\partial x_1}+\lambda_2\frac{\partial G}{\partial x_1}]\tag{5}$$

$$\dot{\lambda}_2=\delta\lambda_2-[(p_2-\lambda_2)\frac{\partial h_2}{\partial x_2}+\lambda_1\frac{\partial F}{\partial x_2}+\lambda_2\frac{\partial G}{\partial x_2}]\tag{6}$$

$$\frac{dx_1}{dt}=F(x_1,x_2)-h_1(q_1,E_1,x_1)\tag{7}$$

$$\frac{dx_2}{dt}=G(x_1,x_2)-h_2(q_2,E_2,x_2)\tag{8}$$

Equation (3-8), when $\dot{\lambda}_i = 0$ and $\dot{x}_i = 0$ ($i = 1, 2$) make up a system of equations, from which it is possible to calculate the optimum stationary values of the NEAC stock and fishing effort.

Under a regime of free access with a limited number of users, the deciding agents are the individual fishermen, who only maximize their discounted profits without taking into account the social value of the natural resource.

Thus under free access situation, we obtain the following first order conditions:

$$p_1 \frac{\partial h_1}{\partial E_1} = c_1 \tag{9}$$

$$p_2 \frac{\partial h_2}{\partial E_2} = c_2 \tag{10}$$

$$F(x_1, x_2) = h_1(q_1, E_1, x_1) \tag{11}$$

$$G(x_1, x_2) = h_2(q_2, E_2, x_2) \tag{12}$$

Equation (9) and (10) express the well known result in the exploitation of a fishery with free entry. Equations (11) and (12) represent the stationary state condition for the fish populations.

Following Clark (1990), we may state that the equilibrium levels of effort exercised by each fleet are higher than those which have just one owner and, to the contrary, the level of stock is lower than the optimum value. In this case, the equilibrium levels for the effort exercised by each fleet are higher than those which have just one owner and, to the contrary, the level of stock is lower than the optimum value.

Following the results obtained we can point out that in order to generate an optimum level of harvesting it is necessary to establish some control on the entry of agents to the fishery. This control could be exercised through the establishment of taxes, either on captures or on fishing effort. We will focus on the case of a tax on effort.

If the regulator decides to establish a tax τ_i, (I = 1, 2), on effort the representative fishermen must decide what the level of effort that maximize

$$\underset{E_i}{\mathrm{Max}} \int_0^{\infty} e^{-\delta t} \{p_i h_i - (c_i + \tau_i) E_i dt,\ i = 1, 2. \tag{13}$$

The following expressions are obtained

$$p_i \frac{\partial h_i}{\partial E_i} = c_i + \tau_i,\ i = 1, 2 \tag{14}$$

If the expressions (3) and (8) are compared, the optimum value of the tax can be obtained as

$$\begin{aligned} \tau_1 &= \lambda_1 \frac{\partial h_1}{\partial E_1} \\ \tau_2 &= \lambda_2 \frac{\partial h_2}{\partial E_2} \end{aligned} \tag{15}$$

System (15) shows that for any fishery with different technologies operating simultaneously leads to the establishment of different levels of tax on effort.

GROWTH AND HARVESTING FUNCTIONS FOR NUMERICAL EXPLORATIONS

For numerical exploration of the general model, we will use particular functional forms of growth and harvesting functions.

Let us assume that recruitment of the mature cod depends on the size of the immature cod stock and stock size of the immature cod depends on the size of the mature cod stock. We also assume that the two sub-stocks interact via cannibalism. Under the above assumptions and following Eide (1997) we may write the growth functions and as follows:

$$
\begin{aligned}
F(x_1, x_2) &= r_1 x_1 (1 - \frac{x_1}{k_1 x_2}) - s x_1 x_2 \\
G(x_1, x_2) &= r_2 x_2 (1 - \frac{x_2}{k_2 x_1})
\end{aligned}
\tag{16}
$$

where r_1 and r_2 are intrinsic growth rates of immature and mature substock respectively, s is the cannibalism attack rate, k_1 and k_2 are positive constants.

Eide (1997) shows that this structure has a close fit to the biological findings regarding the changes in the North-East Atlantic cod stock throughout the 1980's.

Assuming that the harvest function takes a Cobb-Douglas form, h_i (q_i, E_i, x_i) can be expressed as follows:

$$h_i(q_i, E_i, x_i) = q_i E_i^{\alpha_i} x_i^{\beta_i},$$

where E_i is the effort exerted on the ith substock and q_i is the catchability coefficient. To simplify the analysis, it will be assumed that $\alpha_i = \beta_i = 1$.

Since the current-value Hamiltonian is linear in the control variable E_i, the switching functions will determine the optimum level of effort to exert within the fishery. This is traditionally viewed as a bang-bang equilibrium (Kamien and Schwartz, 1991). The switching functions are $\theta_i = (p_i - \lambda_i) q_i x_i - c_i$ (I = 1, 2). If $\theta_i > 0$, then $E_i = Ei_{max}$ and if $\theta_i < 0$ then $E_i = 0$. In the case that $\theta_i = 0$ we get the following equations,

For a system like (10), two symmetric Golden Rules can be derived as:

$$
\begin{aligned}
&(\delta + \frac{r_1 x_1}{k_1 x_2})(p_1 - \frac{c_1}{q_1 x_1}) - \frac{r_2 x_2^2}{k_2 x_1^2}(p_2 - \frac{c_2}{q_2 x_2}) = p_1 q_1 E_1 \\
&(\delta + \frac{r_2 x_2}{k_2 x_1})(p_2 - \frac{c_2}{q_2 x_2}) - (\frac{r_1 x_1^2}{k_1 x_2^2} - s x_1)(p_1 - \frac{c_1}{q_1 x_1}) = p_2 q_2 E_2
\end{aligned}
$$

We next provide numerical simulations. The numerical analysis will be based on the following parameters:

r_1 = 0.5003
r_2 = 0.6728
k_1 = 8.7608
k_2 = 1.1880
q_1 = 0.006650 per vessel
q_2 = 0.001175 per vessel
p_1 = 7579 NOK/tonne

p_2 = 8655 NOK/tonne
c_1 = 18.602103 million NOK
c_2 = 1.452341 million NOK
s = 0.2023

Parameters r_i, k_i (I = 1, 2) and s are taken from Eide (1997). Other parameters are taken from Armstrong and Sumaila (2000).

For free entry case the stationary solution for the cod stock is 0.36908 and 0.142811 million tones for immature and mature species respectively. The stationary solutions of the relevant variables for different levels of the discount rates are shown in Table 1.

In all cases, for discount rates, the optimum stationary solution, for sole owner, is reached for greater levels of stock than the stationary solution for free entry. It is observed from Table 1, as discount rate goes up i.e., greater value is placed on the present than future, the optimum biomass level and total catches decreases. Also it is observed that the greater the stationary level of the cod stock the greater will be the optimum level of catches for the coastal vessel. This is the consequence of the greater relative weight of the stock as regards effort in the coastal production function.

Table 2 provide the optimal equilibrium taxes for different discount rates. We observe that the greater discount rate leads the lower stationary levels of the biomass and a lower shadow price, the tax per unit effort decreases for both the fleets. It is also observe that tax rate on trawling is greater than coastal fleet in all four cases of discount rates.

From our analysis it is clear that the current value of the NEAC biomass is well below the optimum equilibrium level obtained in each scenario. So the fishery is not being exploited in efficient way. Therefore, so that the fishery can be set at an efficient steady state solution, it is necessary to reduce the present pressure on the stock.

Given the functional forms used and assuming that the fishing effort is transferable the shortest possible way to reach the optimum equilibrium level is the bang-bang controls, i.e., zero activity rates for both the fleets until the resource recovers its optimum levels.

Once the cod stock recovers to the optimum equilibrium level, to ensure sustainable exploitation from then on, efficient effort tax must be introduced by each fleet. For δ = 0.01, 0.07, 0.1, 0.2 we get the optimal taxes are (168.32, 12.58), (140, 10.95), (126.8, 10.130) and (91.57, 7.49), respectively. Earning from these taxes could be put back into the fishery.

If we check the stock size of cod from 1946 to 2000 (Wikan and Eide, 2004) we observe that about 70-80% of the cod stock was immature and about 70% catches was taken from immature cod stock. In the year 2004, estimated cod stock size was 1.6 million tones.

Estimations of the Table 3, 4 and 5 were made by using the approximations

$$x_1(t+1) - x_1(t) = r_1 x_1(t)\left(1 - \frac{x_1(t)}{k_1 x_2(t)}\right) - s x_1(t) x_2(t) - TAC_{x_1}$$

$$x_2(t+1) - x_2(t) = r_2 x_2(t)\left(1 - \frac{x_2(t)}{k_2 x_1(t)}\right) - TAC_{x_2}.$$

Table 1: Optimum stationary solutions for different discount rates

δ	x_1 (Million tones)	x_2 (Million tones)	Total (Million tones)	h_1 (Million tones)	h_2 (Million tones)	Total catch	λ_1 (NOK/ tonne)	λ_2 (NOK/ tonne)
0.01	3.71	1.38	5.090	0.251	0.638	0.889	6825	7759
0.07	3.147	1.22	4.367	0.334	0.553	0.887	6690	7641
0.1	2.88591	1.1395	4.025	0.361	0.511	0.872	6609	7570
0.2	2.12	0.88	3.00	0.39	0.38	0.770	6259	7250

Table 2: Optimum taxes for different discount rates

δ	τ_1 (NOK/vessel)	τ_2(NOK/vessel)
0.01	168.38	12.58
0.07	140.00	10.95
0.1	126.80	10.13
0.2	91.57	7.49

Table 3: Transitory steps for zero TAC. Initial values are taken as $x_1 = 1.0854$, $x_2 = 0.2264$ from the year 2000 (Wikan and Eide, 2004)

Year	x_1 (Million tones)	x_2 (Million tones)
1st	1.2816	0.352
2nd	1.565	0.534
3rd	1.917	0.790
4th	2.304	1.137
5th	2.660	1.580
6th	2.880	2.260

Table 4: Transitory steps for zero TAC. Initial values are taken as $x_1 = 1.12$ (70% of 1.6), $x_2 = 0.48$ (30% of 1.6) from the year 2004

Year	x_1 (Million tones)	x_2 (Million tones)
1st	1.4223	0.6864
2nd	1.7680	0.9606
3rd	2.1231	1.3113
4th	2.4258	1.73487
5th	2.5944	2.1994

Table 5: Transitory steps with TAC_{x1} = 0.01911 (70% of 27300 tonnes) and TAC_{x2} = 0.00819(30% of 27300 tonnes). Initial values are taken as $x_1 = 1.12$, $x_2 = 0.48$ from the year 2004

Year	x_1 (Million tones)	x_2 (Million tones)
1st	1.4032	0.67825
2nd	1.7278	0.94072
3rd	2.06307	1.2754
4th	2.3532	1.67877
5th	2.5238	2.1218

In 2003, ICES stated that there is a high risk of stock collapse if current exploitation levels continue and recommended a zero catch during 2004. However Agricultural and Fisheries Ministers from the council of the European Union endorsed the EU/Norway agreement and set TAC as 27300 tonnes. From both the social and political point of view, the ICES recommendation would not be feasible. Our result also shows that if it use the TAC prescribed by the Agricultural and Fisheries Ministers, it will not take much more time to recover in the optimal stationary states. Approximate time of reaching the optimal stationary state would be four to five years depending on the discount rates applied.

DISCUSSION

Fisheries are subject to several kind of risk. One is the risk of a serious stock decline or collapse. This risk is normally increased with reduced stock size.

The problem the fisheries manager has in setting the correct fisheries tax rate.

Once the fish population recovers to the optimum level, to ensure an efficient and sustained exploitation from then on, efficient effort tax must be introduced depending on the discount rates.

Some difficulties are associated with taxation in fisheries. At the first, fishermen are always unanimously opposed to it. They would still receive zero rents, or at best inframarginal rents and the marginal fishermen would be eliminated entirely. The economic rents, now optimized, would accrue to the taxation authority. A second difficulty regards calculation of the optimal tax, which would require the management authority to know the operating cost structure as well as the biological characteristics of the fish population. Since real fish populations tend to fluctuate unpredictably, the optimal tax would have to be recalculated each fishing season.

The fisheries model employed in this paper is quite simplified. Many important variables such as the environmental effects and predation from other species are disregarded. Hence, the results obtained in this study should be taken with care. However, this result may serve as a guideline.

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